TRIBOLOGICAL BEHAVIOR OF HEAT TREATED SPHEROIDAL GRAPHITE CAST IRON

Thesis submitted in partial fulfilment of the requirements for the award of the degree of

Master of Technology

In

Mechanical Engineering

[Specialization: Steel Technology]

Submitted by

Mohammad Salim

Roll No-**213MM2487**

Department of Metallurgical and Materials Engineering

National Institute of Technology

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Certificate

This is to certify that thesis entitled, "**Tribological behaviour of heat treated spheroidal graphite cast iron**" submitted by **Mohammad Salim** (213MM2487) in partial fulfillment of the requirements for the award of Master of Technology Degree in Metallurgical and Materials Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other university/ institute for award of any Degree or Diploma.

Date:
Place: Rourkela

Prof. S.C. Mishra
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AKNOWLEDGEMENT

I would like to express my deep sense of gratitude and respect to my supervisor cum Head of Department Metallurgical and Materials Engineering **Prof. S.C. Mishra** for his invaluable guidance, motivation, constant inspiration and above all for his ever co-operating attitude that enabled me in bringing up this thesis in the present form. I consider myself extremely lucky to be able to work under the guidance of such a dynamic personality and for providing me necessary facilities in the department.

I would like to thank **Ranjan Behera** (Ph.D. Scholar, Department of Metallurgical and Materials Engineering), and my all friends with whose additional help in this study has been a succulent one.

My very special thanks go to all my family members. Their love, affection and patience made this work possible and the blessings and encouragement of my beloved parents greatly helped me in carrying out this research work.

Date:

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ABSTRACT

The main aim of this project is to investigate the microstructures of different matrix samples and correlate to the wear system response by varying matrix microstructure. SG iron is used for the production of different automobile parts such as camshaft and gears. SG iron is most important member among different members of cast iron family due to its high strength, toughness together with ductility. The main reason of this high ductility is presence of nodular structure of graphite that is present in it unlike present in grey cast iron as the flakes. In grey cast iron, stress concentration is high at the corners of these flakes but has been removed in the case of spheroidal graphite cast iron with the nodular shape. As a result of this its ductility increases along with toughness. In order to obtain the optimum wear resistance of SG cast iron, the current investigation involves annealing, normalizing, quench & tempering and austempering heat treatments leading to transformation of as-cast matrix to ferritic, pearlitic, tempered martensitic and coarse upper bainitic matrices respectively. Specimens having different alloying elements were austenitized to 1000°C for soaking time 90 min, followed by furnace cooling, air cooling, oil and salt bath quenching followed by air cooling for respective heat treatments. Vickers hardness test was conducted over the samples under 20Kg followed by wear test was carried over DUCOM TR-208 M1 ball on plate type wear monitor under 10N, 30N and 50N loads respectively in dry sliding condition for the sliding distance of 7.54m with the speed 0.063m/s. The hardness was maximum for quenched & tempered specimen in case of SG-02 samples due to presence of tempered martensitic matrix phase while, in case of SG-01, normalized specimen has maximum hardness due to presence of pearlitic matrix phase. The lowest hardness was observed to be for annealed sample with ferritic matrix phase. On the other hand hardness of ferritic, pearlitic and bainitic matrices was observe to be in between these range, also marginal difference was observed in as-cast and tempered martensitic matrices. The cause of this difference is that in as-cast specimen of

SG-01 has bull's eye ferritic/pearlitic matrix which may cause its hardness increases, whereas in case of as-cast sample of SG-02 fully ferritic phase is obtained as a result of which hardness decreases. For quench & tempered as well as austempered specimens of SG-01 has lower hardness value in comparison of that of in SG-02 because of more percentage of C, Mn, Ni, Cr, Mo and Si in SG-02 specimens that has tendency of strengthening solid solution of ferrite in ductile cast iron. It was observe that when sample of as-cast specimen subjected to load in between 10N- 20N it lost its weight continuously, while with increase in load to 30N subsequently weight gain was observe. This weight gain is due to the formation of oxide layer. There was no weight loss or gain observe for normalized specimen however in case of austempered specimen weight gain was observe for 20N and 30N due to formation of oxide which can be investigated by means of EDAX analysis. Finally it has been concluded that for the samples having ferritic, pearlitic, bainitic matrices phase, adhesive wear is main wear mechanism along with shallow pits are produced due to delamination and deposited over the sites where graphite nodules have already formed before.

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Chapter 1

Introduction

1.1. INTRODUCTION:

Ductile iron is known as spheroidal graphite cast irons which is developed over the past few years, which is of considerable current attention. The maximum verity of cast iron is brittle in nature but spheroidal graphite cast iron is more famous due to its more impact and fatigue resistance. High impacts as well as fatigue resistance properties are due to presence of nodular graphite inclusion. In ductile iron, the graphite is in the form of nodules instead of flakes. The stress concentration is created in matrix due to sharp shape of flakes. Nodules are formed due to use of elements which promotes the nodulizing, such elements are magnesium, cerium, tellurium etc. For nodulizing purpose magnesium is most widely used which boiling temperature is 1100˚ whereas melting temperature of iron is 1500˚C. SG iron is used instead of steel due to its properties like strength, machinability toughness as well as low cost. In industries wear creates more problems consequently the replacement of components need frequent. Due to variation in the matrix, the strength of SG iron can be changed. SG iron, having ferritic microstructure, is softer and gives large elongation while SG iron having pearlitic microstructure, is tough and harder. Through proper heat treatment, strength and hardness of the SG iron can be improved. Ductility is increases using annealing process by converting the parent matrix in to ferritic phase whereas when follow the austenizing process, toughness and hardness increases due to obtaining bainitic structure. Bainitic structure may be upper or lower which is totally depends on cooling rate.

SG iron consists of several materials like carbon silicon, manganese, magnesium, phosphorus, copper and iron, which enhances and controls its properties.

1.2. SG Iron background:

SG Iron was invented by Chinese, an archaeologist who was first inventor of cast iron in the 5th century. The compressive strength and its brittle nature are higher in cast iron. Its strength is lower than steel. On account of fragile character it is less utilized where requirement of sharp edge is needed. Under compression and also it is weak where tension applies. Till 15th century in western nations, casting was not accessible in England Henry VIII was first one who started the casting of group in England., bronze cannons are used instead of iron cannon but after the coming of casting system iron cannon comes in trend. Then again, cannon produced by utilizing cast iron material are heavier than cannon made by bronze. Malleable iron was invented in 1943 by Keith Millis. In the era of Victoria general utility things such as road lights, railings, window outlines and so on were fabricated of cast iron. Apart from above uses it is also used in engineering purposes now days. In the research field of cast iron there is developed day by day. Compacted graphite irons are the illustrations of created type of cast iron [1].

1.3. Useful properties of SG cast iron:

1. It has sufficient degree of fluidity as well as capacity to make good casting.
2. At a particular composition, machinability of cast iron is very good.
3. Generally, melting range (1130-1250°C) which is lower than steel.

The chemical composition and rate of casting of cast iron has great influence on both structure and physical properties.

1.4. Chemical composition:

1.4.1. Effect of composition of base iron

(a) Carbon: In iron, the volume of Carbon ranges from 3% to 4%. Despite the fact that the most proficient carbon percentage differs around 3.4 and 3.8 percent. Cast ability is related to the fluidity, it improves by improving fluidity alongside the fluidity influenced by variation in carbon percentage. On amid the last phase of interdendritic shrinkage is brought during the final stage of solidification. With the increase of carbon percentage it is observe that the interdendritic shrinkage can be minimize to great extent. A mathematical statement has been determined which is derived after to assure least shrinkage for capture this shrinkage defects .To capture this shrinkage defect, a mathematical statement has been inferred which is taken after to guarantee least shrinkage, as follows:

$$\boxed{\text{Total carbon}+1/7\text{Silicon}=3.90}$$

In the various percentage of carbon has not much effect on mechanical properties of SG iron. Due to huge reduction in yield strength of spheroidal graphite iron UTS decreases by around 2.48 MPa per 0.1% increase of carbon. It is observe that in case of as-cast specimen Addison of 0.15% carbon, hardness decreases by around 5 numbers while increase in percentage elongation or ductility.

(b) Silicon: Silicon has a tendency to increase the rate of formation of graphite. When it is added to the melt of cast iron then it immediately forms the flakes of graphite in the case of grey cast iron, but when it is added along with the Magnesium and cerium then graphite takes the shape of nodules. Silicon content present in SG iron affects extraordinarily on mechanical properties.

(c) Manganese: Due to presence of manganese in the specimen the refinement of pearlitic phase takes place. At the same time it has tendency to stabilize the pearlitic phase at the sacrifice of the ferrite phase.

(d) Sulphur: Sulphur should be present in the SG iron in limited amount. When the sulphur content is more in the SG iron then it increases the amount of combined carbon in it. As a result of which hardness increases. Reaction of sulphur with magnesium produces MnS which trapped in the casting weakens the casting quality. The greater content of it, affects the nodules of graphite that is advanced by residual magnesium which is regulated by sulphur.

(e) Phosphorus: Phosphorous influences ductility as well as toughness severely and also decreases the impact resistance. When phosphorous will be over 0.08 percent, increases the brittle tough transition temperature. So, in the major part of castings, it should be less than 0.043%.

1.4.2. Alloying elements:

(a) Nickel: Nickel acts as pearlite promoter same as manganese and also a good graphatizer. The presence of nickel ranges 1.0 to1.5% with manganese in suitable content give pearlitic structure in as-cast specimen with free of carbide. Due to pearlite structure a good combination of fatigue strength, wear resistant etc. obtain. For normalized as well as quenched specimen, Ni increases hardenability without any loss of ferritic structure.

(b) Molybdenum: Molybdenum has tendency to increase the pearlitic phase in as cast. It has ability to reduce annealed cycle. Molybdenum is generally used to increase the strength as well as hardness in heavy section castings. Combination of Mo and Ni in a controlled content an acicular structure is developed, which enhances tensile strength as well as toughness.

(c) Copper: It is utilized to a little degree as a composite added before treatment with magnesium. It retarded ferrite and very skilled to stabilize pearlite. When silicon content in lower amount, Copper retards annealing. Copper also retards impact resistance and also increases transition temperature. Formation of spheroidal graphite is affected by it.

(d) Chromium: Chromium increases the wear resistance and hardness.

1.5. Microstructures

The microstructure of graphite creates the difference between SG iron and grey cast iron, graphite becoming in nodular form after suitable heat treatment.

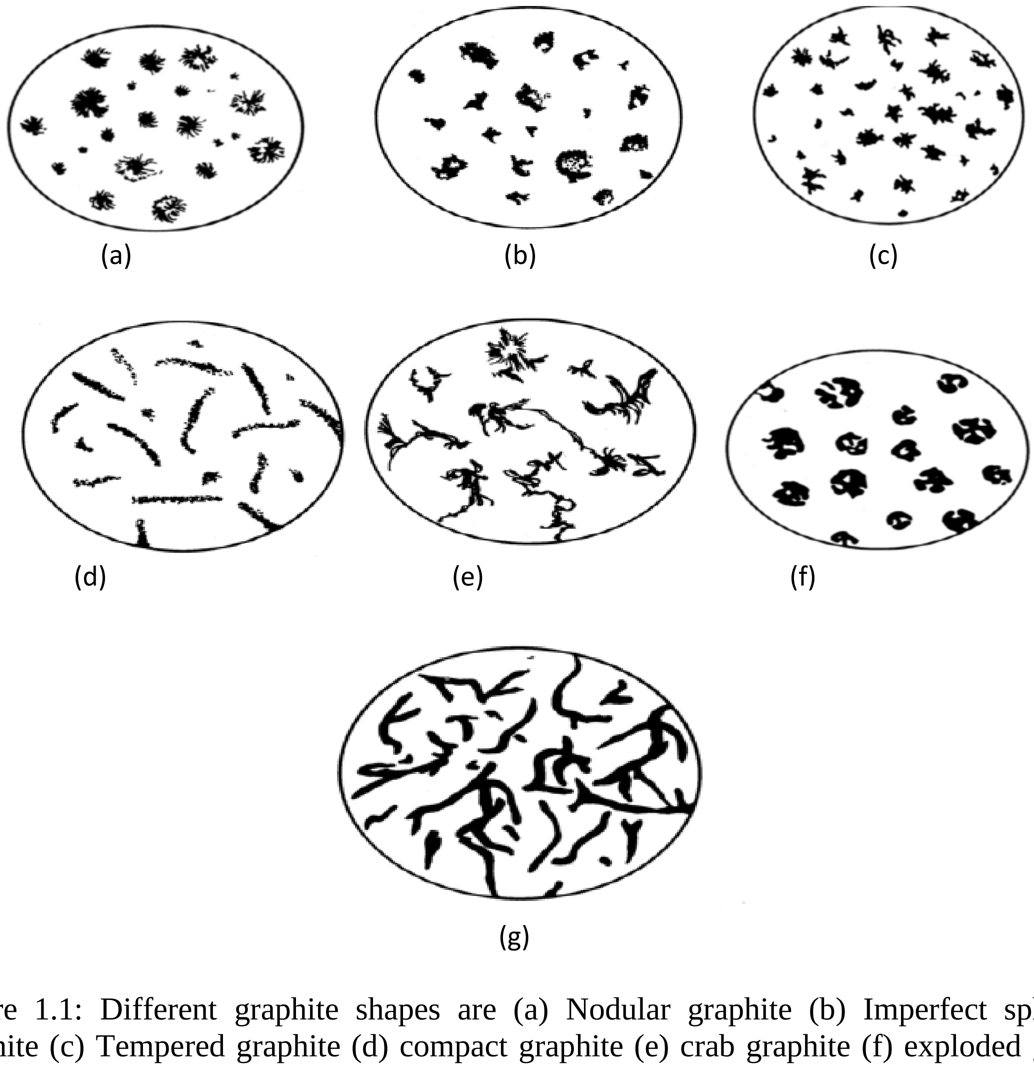


Figure 1.1: Different graphite shapes are (a) Nodular graphite (b) Imperfect spheroidal graphite (c) Tempered graphite (d) compact graphite (e) crab graphite (f) exploded graphite (g) flake shaped graphite

Some important components present in SG iron.

Graphite

It is the main constituent of ductile iron, it presents in cast iron in stable form. It has low density and high thermal conductivity. The main difference of ductile iron in comparison to cast iron is the shape of graphite. The shape of graphite is spherical or nodular while in cast iron, it is in flakes form. Flakes form creates stress concentration.

Ferrite

The phases present in cast iron, ferrite is purest phase. Due to ferritic phase, SG iron has lower hardness as well as strength, but also improves ductility as well as toughness.

Pearlite

Pearlite is obtained by eutectoid reaction, it is a mixture of ferrite and cementite. Pearlite gives a higher strength as well as it decreases ductility, which is required in various applications.

Martensite

It is defined as supersaturated solid solution of carbon in iron which is obtained by rapid quenching. It is brittle as well as hard because of distortion in lattice. Martensite is obtained by shear deformation process.

1.6. WEAR:

Wear is defined as the movement of materials from one position to another position on a solid surface when surfaces are frictional contact to each other. Wear is a serious problem in industries where the equipment is uses to conveying the abrasive material or the surfaces having frictional contact. So it needs to frequent replacement of component.

Wear of metals relies on upon numerous variables, so wear exploration programs must be arranged methodically. Henceforth specialists have standardized a portion of the information to make them more valuable. The wear guide proposed by Lim and Ashby [2] is all that much valuable in such manner to comprehend the wear component in sliding wear, with or without oil.

1.6.1. TYPES OF WEAR;

There are five different kind of wear names are (a) Erosive (b) Abrasive (c) Adhesive

(d) Corrosive etc.

Abrasive wear

It can be found that when two surfaces one is harder and second one is softer slide over each other [3]. According to ASTM International, in abrasive wear material is removed by hard particle that are move along the surface.

On the basis of type of contact as well as environmental contact, it has various types [4]. The common similarity is that of substance being removed or evacuated by a cutting or ploughing process [5].

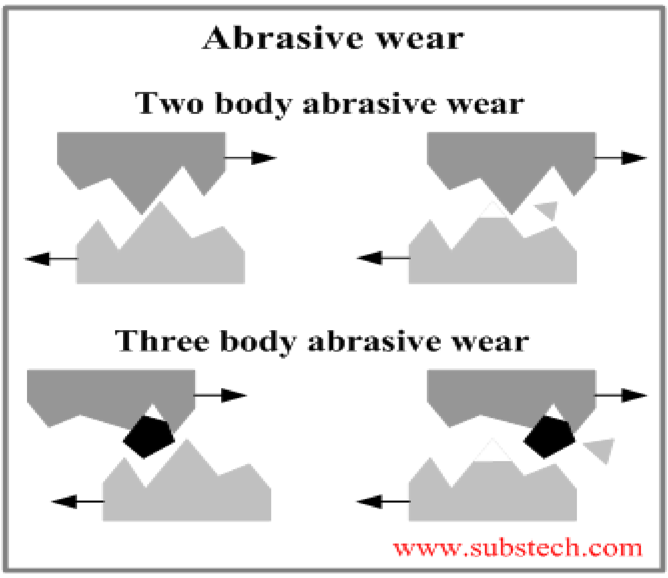


Fig. 1.2: Schematic diagram of abrasion wear mechanism

Adhesive wear mechanism

Adhesive wear may be occurred amid surfaces when they are in contact to each other. It is related to the undesirable movement and also connection of wear wreckage and material transfer from one surface to the next. It is occurred due to plastic deformation of material [6].

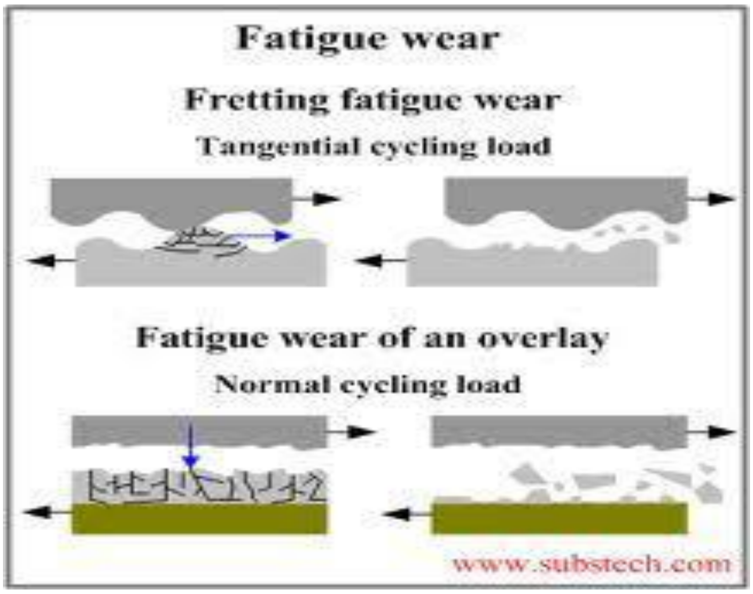


Fig. 1.3: Adhesive wear mechanism diagram.

1.7. Application of SG iron

SG iron is used widely in automobile industries, mining industries and structural industries etc. due to its excellent mechanical properties. A significant part of the yearly generation of SG iron is as malleable iron pipes, utilized for water and sewer lines. It rivals polymeric materials, for example, PVC and polypropylene, which are all so much lighter than steel or SG iron, yet which, being adaptable, require less rushed establishment and insurance from physical harm. Ductile irons are also used in many automobile parts where strength is required greater than aluminium but not like steel. Other major modern applications incorporate off-thruway diesel trucks, rural tractors, and pumps. Ductile iron also used for the fabrication of several components examples pinion, gears, crankshaft etc., so it is essential to pay attention to enhance the wear resistance [7-9].

(a) Manhole assembly

(b) Manhole covers

(c) Pipe fitting

Fig.1.4: SG iron application

Chapter 2

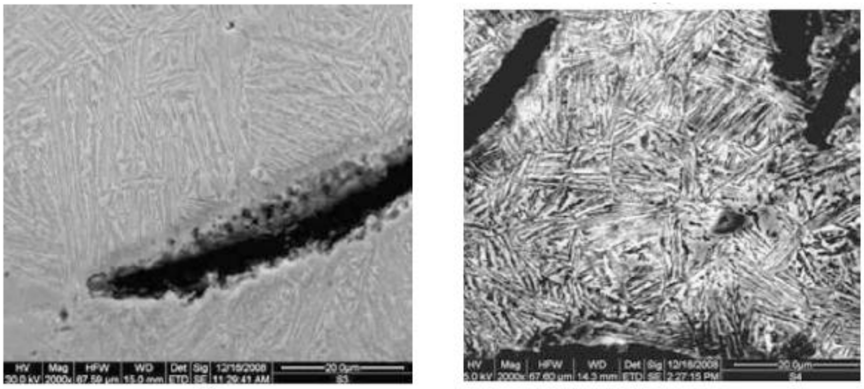
Literature Review

2. Literature review:

2.1. A Brief Discussion about Ductile Iron

Spheroidal Graphite iron can be defined as an alloy of iron consists of graphite found in compact, spherical geometry instead of flakes form. SG iron, usually termed as nodular graphite cast iron. Due to the presence of nodules of graphite, it has high ductility along with the enormous strength. Ductile iron matrix has different forms, ductile iron having ferritic structure is soft, and having pearlitic structure is harder and higher strength.

Aravind Vadiraj et.al. [10] Compared the properties of gray iron alloy in as-cast and austempered specimen at 360°C. It was observe that mechanical strength of austempered specimen had moderately increased than the as-cast gray irons with pearlitic matrix. He also observed about wear behaviour and found that the wear rate of austempered specimen was lower by 7-14 times than pearlitic alloyed iron along with the decrement in friction coefficient. When Ni was added with the cast iron solution it was found that due to addition of it wear resistive capacity increased. It was also observed that tensile strength of cast iron increased, when carbon was added in lower extent. Finally, he concluded that presence of graphite nodules had tendency to improve the wear rate behaviour.



(a) (b)

Fig.2.1: Different Ausferritic microstructure in the austempered cast iron alloys (a) alloy-7 (b) Alloy-4

H.R. Abedi et al. [11] focused on the impact of characteristic of graphite nodule like nodule count, nodularity and nodule size. In order to optimize the wear resistance capacity, he focused on the effect of nodule count of a ferritic–pearlitic ductile iron on its wear behaviour. Ductile cast iron test specimens, ranging from 10 to 50mm of thickness, with the nodule counts of around 150 and 450nod/mm2 were taken. Prior to the wear test it was necessary to perform the heat treatment processes over the sample in order to investigate the microstructures. Wear tests were conducted on a pin-on-disk type machine under dry sliding conditions under the application of loads 1.5, 3.5 and 5.5kgf respectively. Oxidation wear was the main wear mechanism at lower load, while at the higher load adhesive wear was predominant. Meanwhile at the lower load conditions, the specimen had higher nodule count shows lower wear rate than that specimen having low nodule count. But when load was increased then it was found that wear resistance decreased with the increase in nodule count.

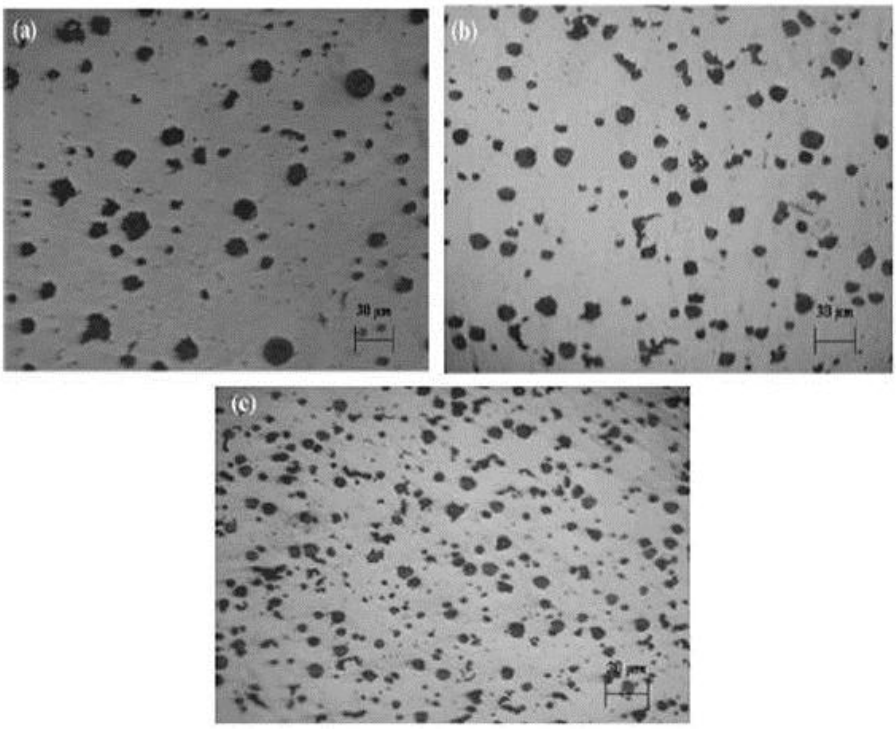


Fig. 2.2: Microstructures of SG iron w.r.t. nodule count (a) 50mm thickness, (b) 25mm thickness and (c) 10mm thickness

Aravind Vadiraj et al. [12] investigated the hardness and wear resistance of specimens in different conditions like austempered, tempered and quenched conditions at different temperature. He made three groups of hypereutectic cast iron alloys with additives Cu, Ti, Nb, and Ni. Cast iron had good wear resistance in tempered and quenched condition, while at 400C, it had moderate hardness. So, that observation was helpful for the comparison of wear resistance of specimens in austempered condition. Further it was investigated that wear resistance of cast iron increased due to presence of Cu in higher extent, while wear resistance of cast iron decreased with the Ni content enhancement. In austempered condition, wear resistance enhanced by increase in Cu percentage and the deficient by increased in Ni content.

R.Arabi Jeshvaghani et al. [13**]** focused about the alloying elements at surface on the microstructure and also the wear phenomena of SG iron in his work study. He told that SG iron specimens were covered by single and two fold pass welds of a nickel based electrode utilizing shielded metal arc welding process then he investigated the effect on wear system and hardness of coated layer on the basis of number of passes. Finally he concluded that the hardness of coated layer was high due to presence of full of austenite phase with little amount of carbides.

G. Straffelini et al. [14] focused on the dry sliding wear of two austempered SG irons, portrayed by distinctive hardness qualities, was researched. The tests were done utilizing plates with 40 mm breadth and 10 mm height. The connected load was in the extent somewhere around 50 and 500 N. Since the introductory Hertzian weights were expansive in light of the line contact, plasticity commanded wear with the arrangement of delamination was acquired. In this way, the treatment cycle of a few samples was directed with the point of acquiring a mild wear amid moving sliding through the development of a surface oxide layer. As an examination, the dry sliding wear of gas nitrided steel was likewise researched. The outcomes demonstrate that the wear coefficients of the samples with the oxide layer on their surface were really mild. On the other hand, the samples created without such a layer showed even lower wear coefficients. Despite the fact that wear was by delamination, wear coefficients were still low in light of the activity of graphite, which had the capacity crush at first glance amid sliding, in this way decreasing adhesional powers. Furthermore, a mechanically blended layer shaped on the sliding surfaces, and this gave an extra increment in the wear resistance. Due to this, the material with lower matrix hardness showed a more noteworthy wear resistance. The wear resistance of the nitrided steel was discovered to be dictated by the external piece of the compound layer, and it was obtain to be lower than that showed by the two ADI.

J. Zimba et al. [15] concentrated his study over the wear behaviour of unalloyed SG iron under the dry sliding condition. The wear test was carried on tribo tester machine under the load of about 40 N–140 N. He demonstrated that when temperature varied from 325°C–

375°C the tribological properties of the unalloyed SG iron was change. Due to increase in wear resistance capacity there was decrease in coefficient of friction. The improvement of wear system was due to the transformation of ausferrite in to martensite.

B. Podgornik et al. [16] suggested that SG iron should have more application because of its good properties like strength, toughness and fatigue endurance as well as its low cost. For this purpose he performed the different heat treatment process for improving wear resistance of SG iron. He extracted a new method in order to improve local reinforcement of SG iron without bargaining other properties which was known as OPTICA.

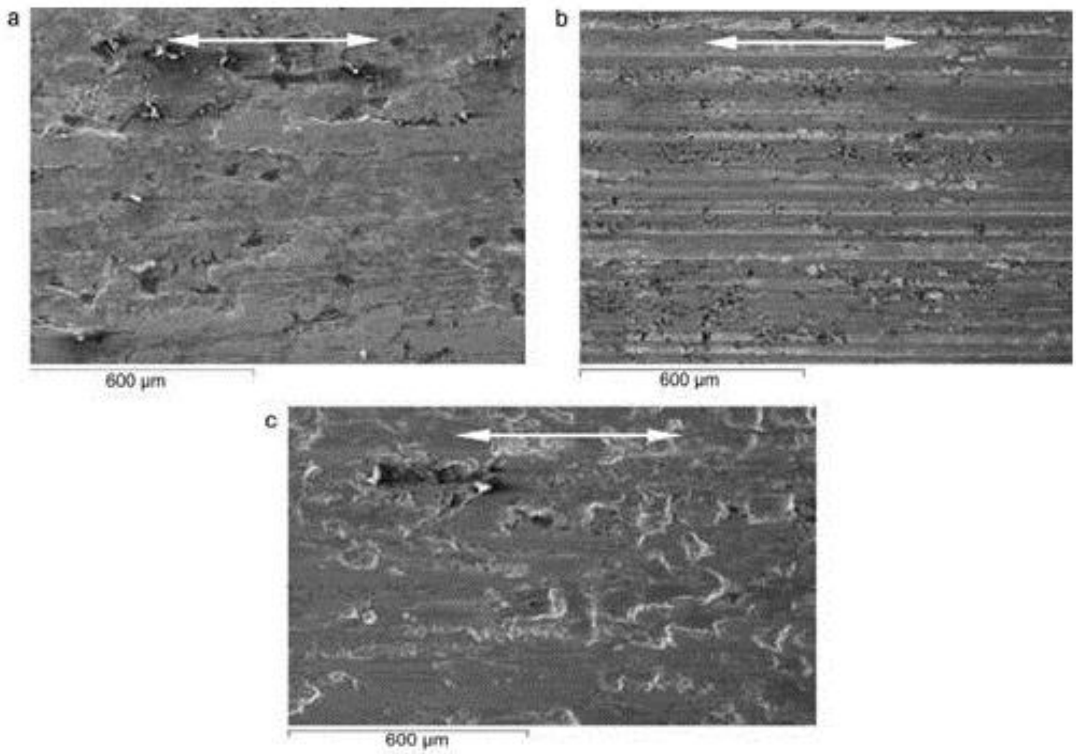


Fig. 2.3: Worn surface of ductile iron in different condition (a) as-cast,

(b) Hadfield grade steel (c) Hardox 500 steel

R. Arabi Jeshvaghani et al. [17] described about the enhancement of wear resistance of ductile iron using surface alloyed layer in his study. In order to do the experiment tungsten inert gases were made to pass through the surface alloyed layer of 3mm thickness deposited on ductile iron surface. After the investigation of microstructure through XRD analysis, Vickers hardness was conducted over the samples and finally he got the carbides scattered in the microstructure of surface alloyed layer. Due to this microstructure, wear resistance and hardness of coating layer has been improved.

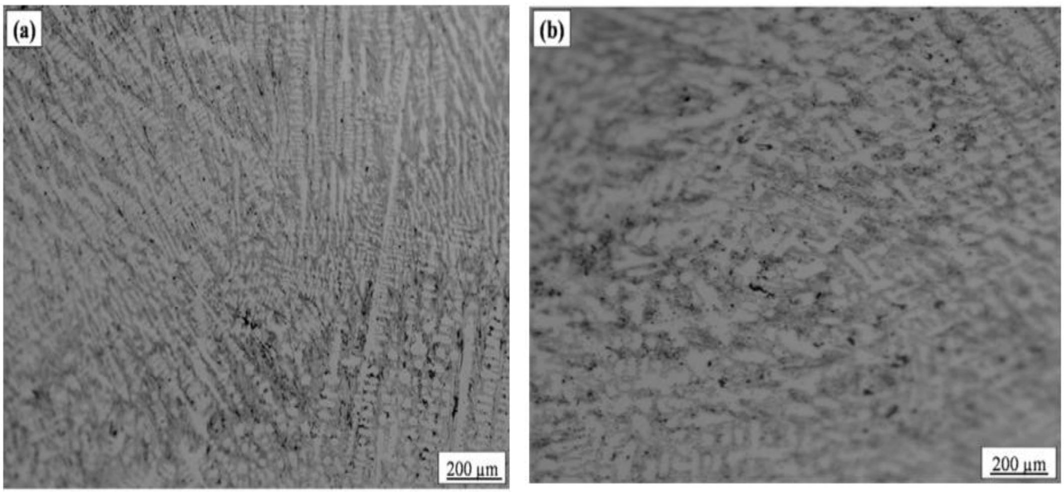


Fig.2.4: Microstructure of surface alloy layer (a) near the fusion line (b) centre of the coating.

Chapter 3

Experimental Procedure

3. EXPERIMENTAL PROCEDURE:

In order to determine the different microstructures and correlates the wear response due to different matrix phases, the following procedure is carried out. Experiments are performed over the samples of different composition represented by SG-01 & SG-02 is shown in tables below. Prior to the wear response and characterization of specimens, oxide layers are rubbed out with the help of machining process.

3.1. Composition of test specimen are given below:

Table 3.1: chemical composition of SG iron in wt. %

Alloy	Elements (in wt. %)											
	C	Si	Mn	S	P	Cr	Ni	Cu	Mo	Mg	Ce	Fe
SG-01	3.45	2.07	0.15	0.008	0.024	0.02	0.15	----	----	0.043	----	Rest
SG-02	3.61	2.10	0.20	0.007	0.022	0.03	0.47	0.009	0.001	0.043	0.004	Rest

3.2. Heat treatment

Heat Treatment is the process in which metals are heating as well as cooling in a controlled way to amend their physical as well as mechanical properties without altering the item shape.

Heat Treatment is regularly associated with enhancing the feature of material however it can similarly be utilized to modify certain manufacturability targets, for example, enhance machining, enhance formability etc. Along these lines it is an exceptionally empowering manufacturing process that can help other assembling methodology, as well as improve product execution by growing quality.

3.2.1. Annealing:

Annealing is a process that changes the properties of metals in physical as well as chemical to enhance ductility of material and to make more formable. Specimen was initially heated to a temperature of 1000°C (austenizing temperature) and hold there for 90 minutes, then decreasing the temperature to the temperature of 700°C and hold there for 5 hours 30 minutes, followed by cooled in furnace to room temperature.

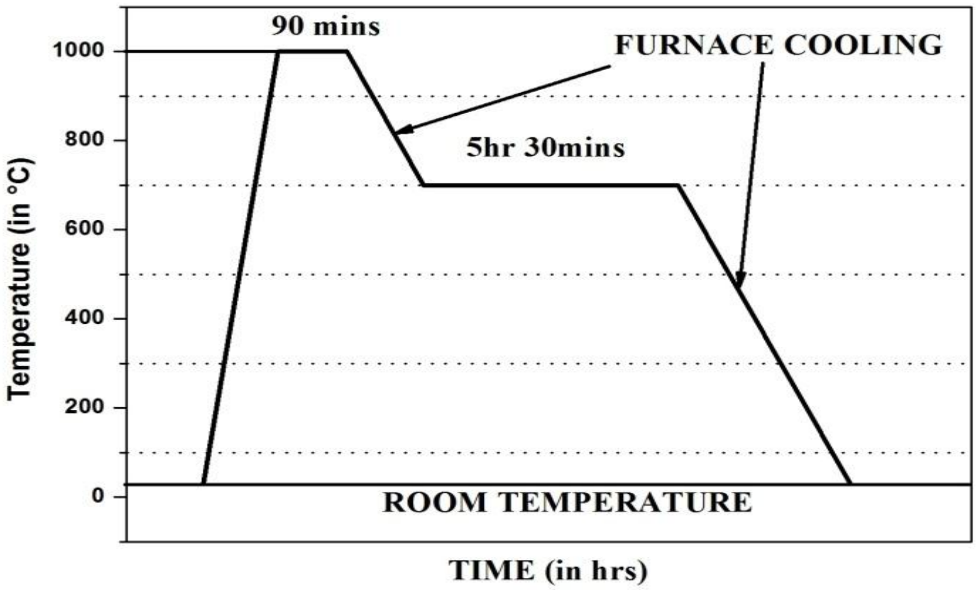


Fig.3.1: Annealing heat treatment process

3.2.2. Austempering:

Austempering is the process of heat treatment, basically applied for ferrous materials, like steel and SG iron. The bainite microstructure is obtained for steel while ausferrite is obtained in cast iron. To improve mechanical properties, it is used.

In the Austempering process, the specimen was heated to 1000°C and hold for 1 hour 30 minutes. Then the sample was quenched in salt bath. Quenched salt bath is the mixture of

KNO_3 and $NaNO_3$ in 1:1 ratio at 500°C. Further the sample hold for 4 hours in the salt bath followed by air cooling to room temperature.

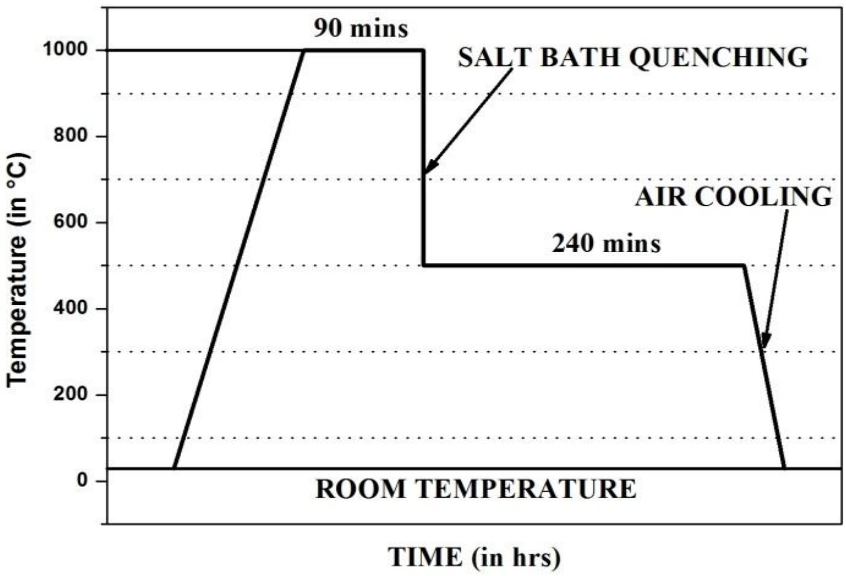


Fig.3.2: Austempering heat treatment process

3.2.3. Quench & Tempering

Sample was heated to Austenising range (1000°C) and soaking for 1 hours and 30 minutes, then the sample is quenched in mineral oil maintained at 100°C, getting martensitic structure. Sample is tempered at 500°C for 2 hours, then air cooling to room temperature.

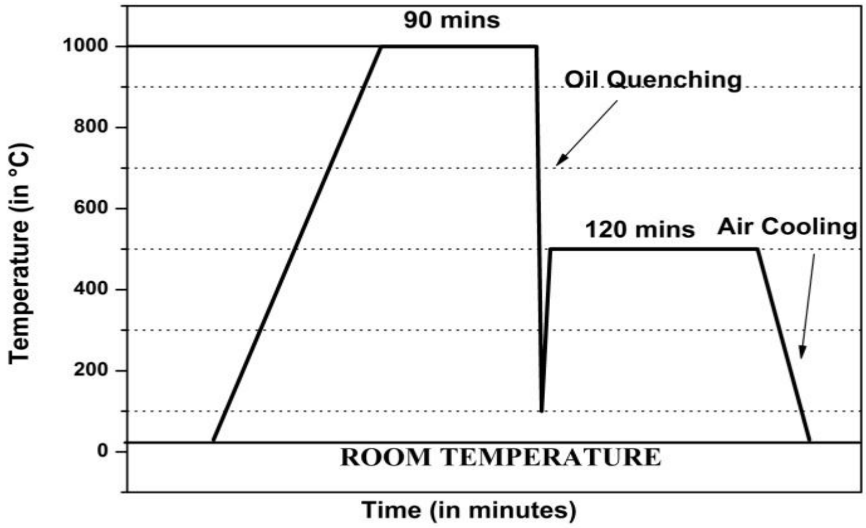


Fig.3.3: Quench & Tempered heat treatment process

3.2.4. Normalizing

Normalizing is the process to improving ductility and machinability of SG iron. Sample is heated 1000°C and hold there for 1 hour 30 minutes followed by air cooling to room temperature.

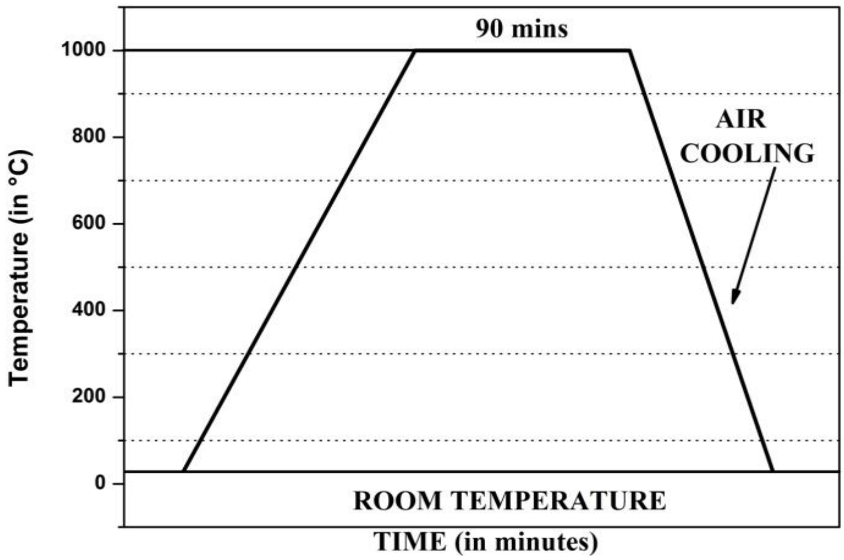


Fig.3.4: Normalizing Heat treatment process

3.3 Characterization

3.3.1 Optical microscopy

Optical microscopy analysis was opted for characterization of different as-cast and heat treated specimens. Optical microscope along with image analyzing software is used to investigate the morphological aspects of specimens. Before investigation sample were polished with belt polisher followed by different grades of emery paper and diamond polishing technique. After polishing specimens were etched with 2% Nital solution and the microstructure was observed under 100X magnification and the morphological parameters were determined by the help of image analyzer.

Fig.3.5: Computer Integrated Optical Microscope

3.4. X-Ray Diffraction

To obtain plane as well as crystal structure of sample, the XRD Technique is commonly used with the help of X rays. In XRD analysis JCPDS is supposed to be the references on the basis of which the peaks are obtained and plotted via ORIGIN PRO8.0. The graph is drown on the basis of the above information in such a way that Intensity is along Y-axis and 2ϴ is along X-axis.

Fig.3.6 XRD Machine

3.5. MECHANICAL TESTING

3.5.1. Vicker's hardness test

Vickers hardness was conducted by applying 20Kg and keeping dwell time 10seconds for every heat treated as well as as-cast specimen.

Fig.3.7: Vicker's Hardness Tester

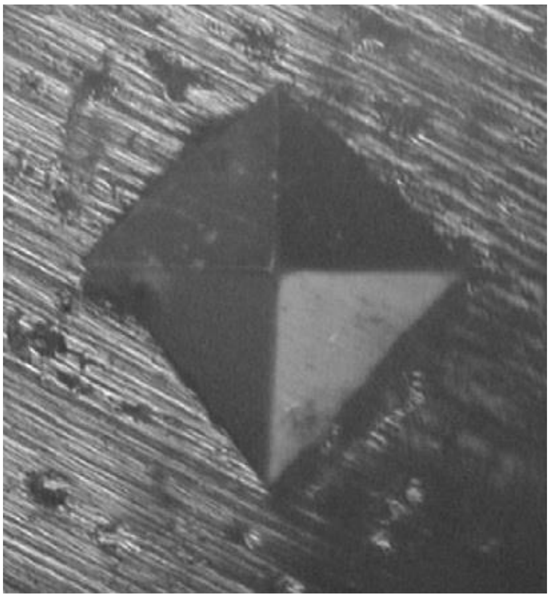


Fig.3.8: Specimen showing indentation

3.5.2. Wear Test

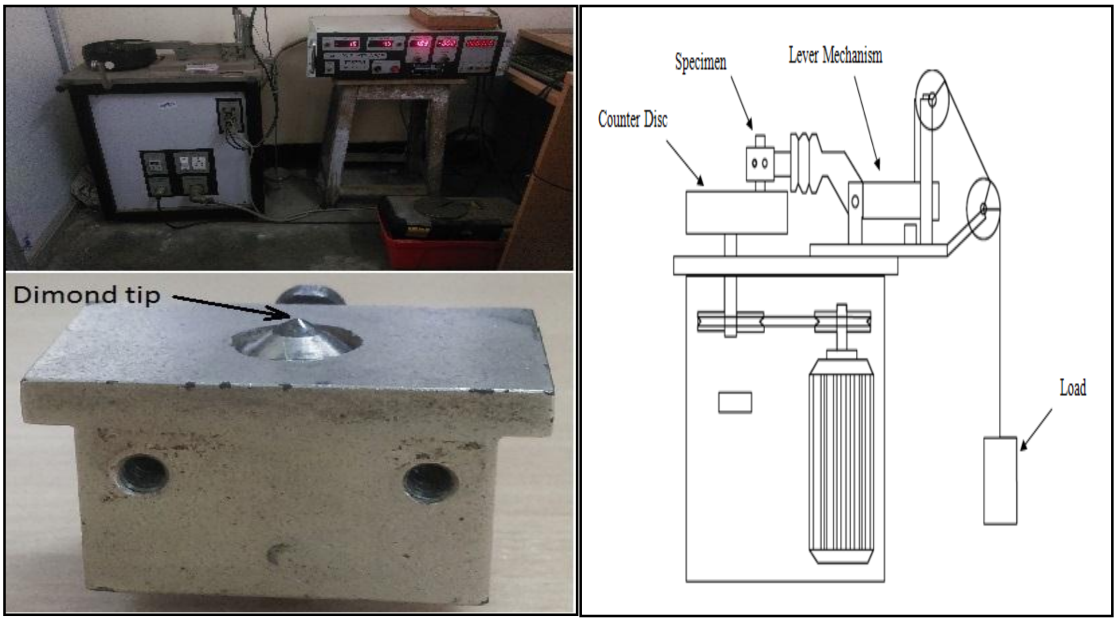


Fig.3.9: (a) Ducom TR-208-M1 Ball on plate type wear monitor

(b) Schematic diagram of pin on disc wear test machine [19]

Ball on plate type wear tester was used in order to investigate the response of the wear system of specimens that is as-cast as well as heat treated. It is a type of wear tester having diamond tip. To conduct wear test, load is taken as 10N, 30N, 50N for sliding span of 7.54m and0.063m/s linear velocity. Using the electronic balance which accuracy is 0.01 mg, weight loss is measured. Cleaning of specimen is done with the help of acetone .While wear is performed over the sample the specimen surface should be flat, whereas indenter used was diamond cone of angle 120° together with 0.4mm diameter of tip [18-21].

3.6. FESEM

FESEM stands for Field emission scanning electron microscopy, in which a narrow beam having low and high energy is emerged by electron gun cathode of scanning electro-microscope, this beam strikes on the sample surface, and after interaction it produces image of that particular area. In comparison to scanning electron microscopy it created a clear, good resolution and less distorted images. FESEM has ability to investigate the contamination spots with the help of Energy Dispersive X-ray Spectroscopy.

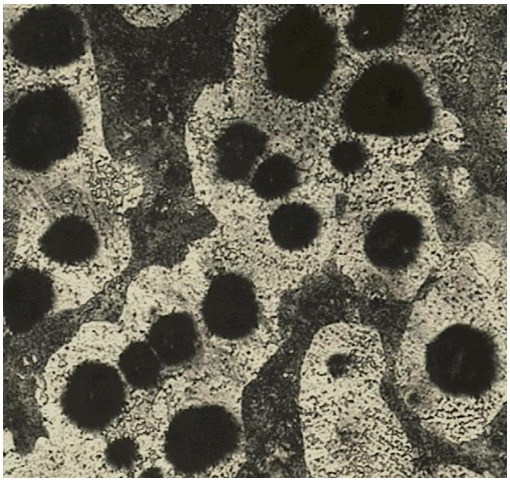
Chapter 4

Result and Discussion

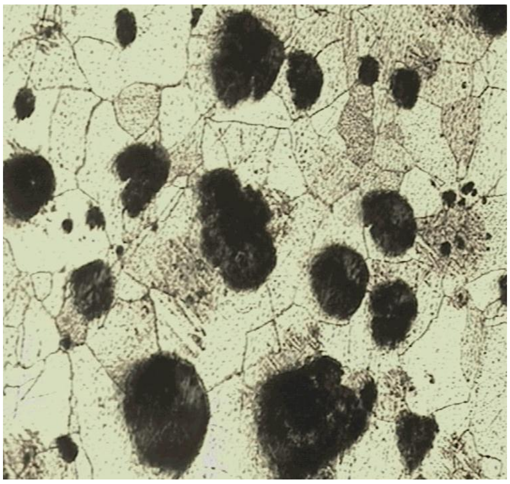
4. RESULTS AND DISCUSSIONS:

4.1 Microstructural analysis

In order to investigate the microstructures of different matrix phases of SG-01 & SG-02 compositions and to establish the relation between matrix microstructures and wear mechanism the whole project has been carried out. The images of different matrix microstructures are shown below

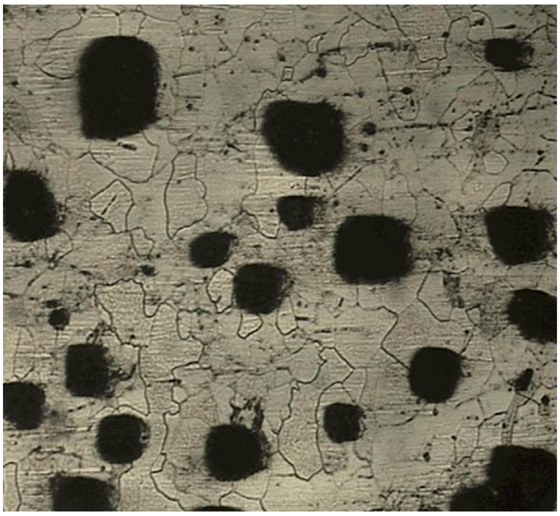


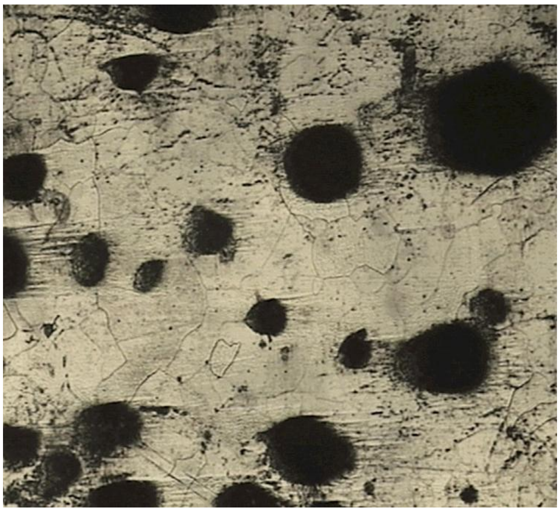
(a) As-cast specimen SG-01



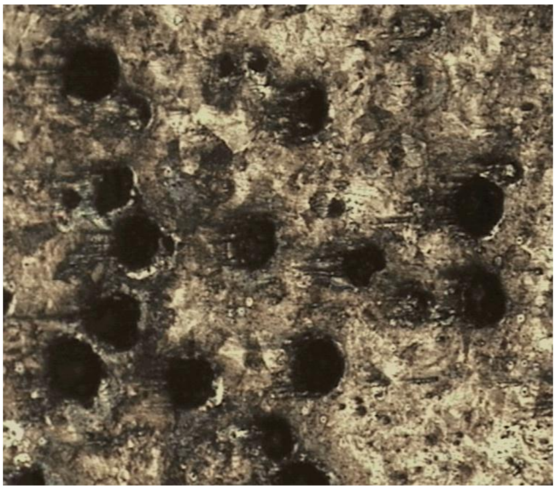
(b) As-cast specimen SG-02

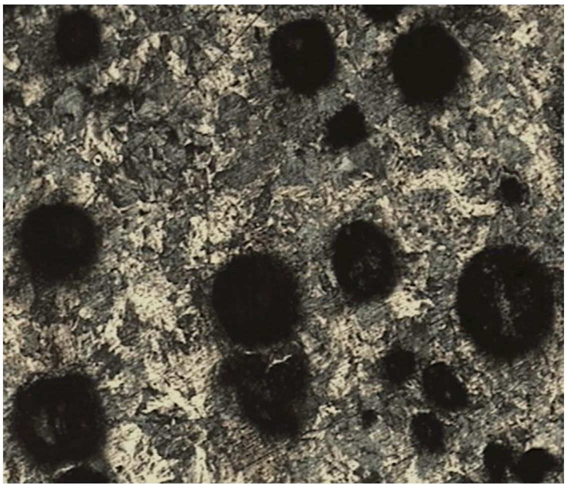
The microstructures of both SG-01 and SG-02 as cast specimens were shown in figure (a) & (b) respectively above. In the former one microstructure is of bull's eye ferrite/ pearlite type in which graphite nodules are surrounded by ferrite rings with the pearlite matrix phase, whereas in later one graphite nodules are present in fully ferrite matrix phase. This is attributed to the fact that SG-02 has more silicon percentage than that of SG-01 composition. Presence of silicon in more extent is responsible for the promotion of ferrite phase (it increases the tendency of dissolution of carbon atoms in the specimen). Although Mo, Ni and Cr are also present in the SG-02 composition that increase the pearlite phase, but presence of silicon content in higher extent diminishes the effect of them. On the other hand after annealing treatment the as-cast matrix transformed to fully ferritic matrix shown in figure (c) & (d).





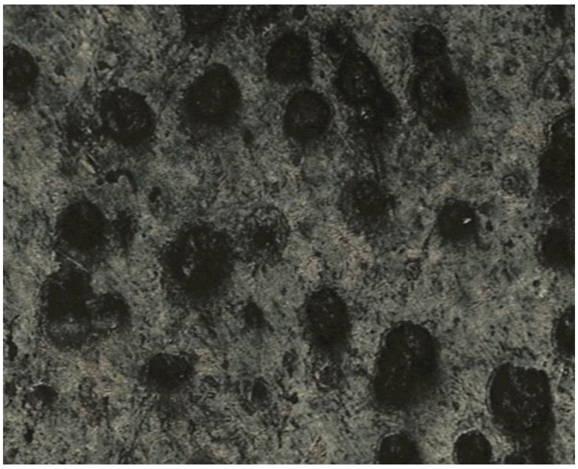
(c) Annealed Sample SG-01 **(d) Annealed Sample SG-02**



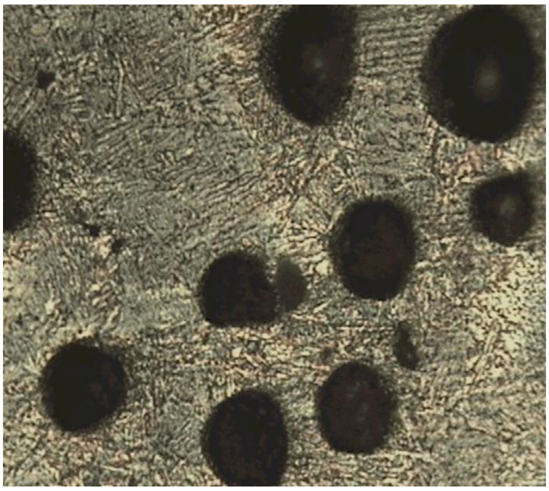


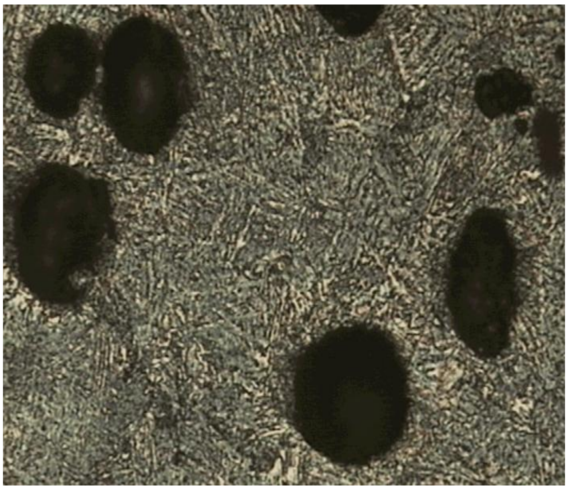
(e) Normalized Sample SG-01 **(f) Normalized Sample SG-02**

Microstructure of Normalized sample of SG-01 & SG-02 compositions are investigated as well as shown in figure (e) & (f). The graphite nodules are surrounded by the ferrite/pearlite matrix, in SG-01 specimen pearlite phase is more than SG-02 specimen; reason is that Si content is more in SG-02 specimen than SG-01. Silicon promotes the formation of ferrite phase. The microstructure obtained for quench & tempered, figure (g) & (h) and austempered specimen figure (i) & (j) are tempered martensitic and upper coarse bainitic respectively. From the quantitavie microstructure analysis it was revealed that proeutectoid ferrite is present in every specimen of alloy SG-02 due to the higher amount of Si, Mo, Cr which not only promotes the ferrite formation but also stabilize it. Further from quantitative metallographic analysis it was observed that with increase in cooling rate from the austenitizing stage the carbon diffusion and migration is restricted resulting in more no of nucleation site for graphite nodules and hence the nodule count is increased in normalized, quench & tempered and austempered specimens for both the alloys.



(g) Quenched &Tempered sample SG-01 **(h) Quenched & Tempered specimen SG-02**





(i) Austempered specimen SG-01 **(j) Austempered specimen SG-02**

Fig 4.1: Microstructures of SG-01 & SG-02 samples in different heat treated condition100X

Table 4.1: Nodularity (%), Nodule Count and Graphite Area Fraction (%) of SG-01 and SG-02 specimens

Alloy			SG-01				
			As-cast	Annealed	Normalized	Quenched & tempered	Austempered
Microstructural Entities	Nodularity		96%	99%	97%	89.5%	94%
	Nodular count (mm^2)		19	23	37	48	57
	Area Fraction	F	48%	80%	19.5%	2.5%	--------
		P	13.6 %	--------	65.5%	---------	---------
		G	38.4 %	20%	15%	40%	23%
		M	------	-------	--------	57.5%	--------
		B	-------	-------	-------	--------	77%

Alloy			SG-02				
			As-cast	Annealed	Normalized	Quenched & tempered	Austempered
Microstructural Entities	Nodularity		94%	95.5%	95%	98.5%	90%
	Nodular count (mm^2)		33	25	35	65	58
	Area Fraction	F	71%	75%	21.5%	--------	--------
		P	-------	--------	46.5%	---------	---------
		G	29%	25%	32%	24%	24.5%
		M	------	-------	--------	76%	--------
		B	-------	-------	-------	--------	75.5%

4.2. X-ray Diffraction Analysis

X-ray diffraction investigation leads to the confirmation of matrices observed under optical microscope for respective specimens. It was found that except austempered specimen all other heat treated specimen along with as-cast specimen has BCC crystal structure which is in complete agreement with the phases obtained. Whereas the austempered specimen is appeared to have both FCC and BCC crystallographic planes confirming the presence of ausferrtic phase.

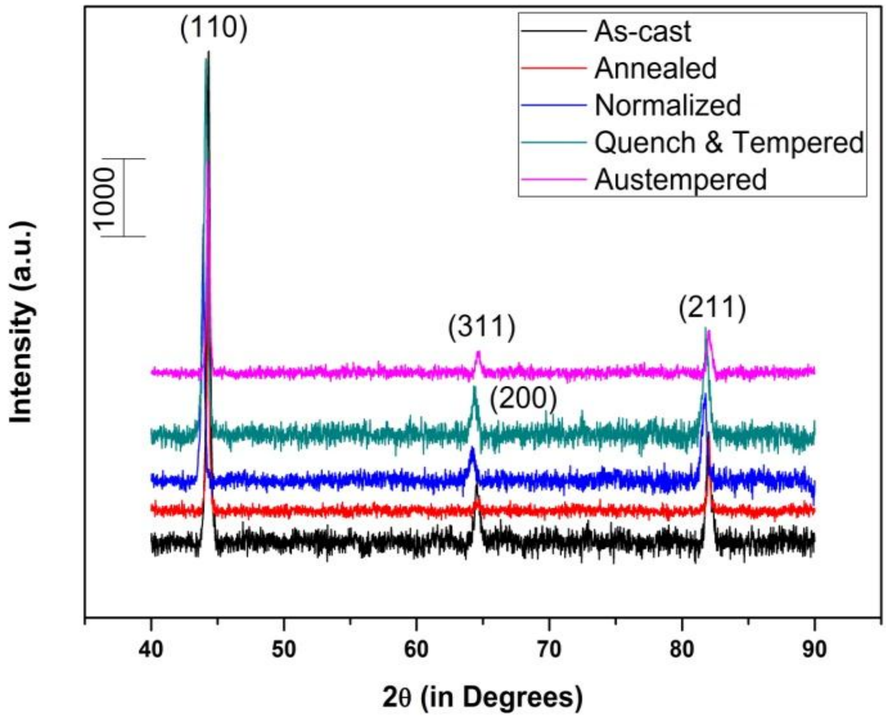


Fig.4.2: Comparison of XRD images of as-cast, annealed, austempered, normalised and quenched& tempered specimen

4.3. Hardness and Wear System Analysis:

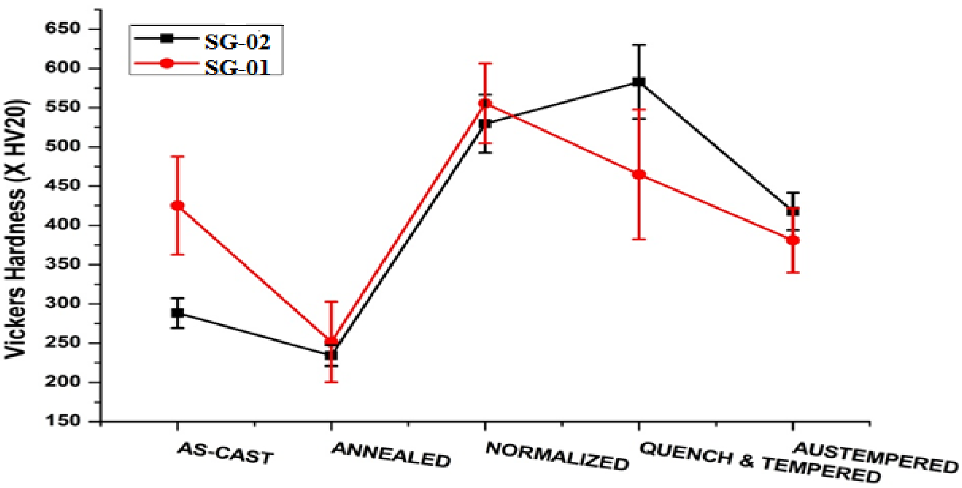


Fig.4.3: Hardness comparison of SG-01 and SG-02 specimen at different conditions

The hardness was maximum for quenched & tempered specimen in case of SG-02 samples due to presence of tempered martensitic matrix phase while, in case of SG-01, normalized specimen has maximum hardness due to presence of pearlitic matrix phase. The lowest hardness was observed to be for annealed sample with ferritic matrix phase. On the other hand hardness of ferrite, pearlite as well as bainite matrices was observe to be in between these range, also slight difference was observed in as-cast and tempered martensitic matrices. The cause of this difference is that in as-cast specimen of SG-01 has bull's eye ferritic/pearlitic matrix which may cause its hardness increases, whereas in case of as-cast sample of SG-02 fully ferritic phase is obtained as a result of which hardness decreases. For quench & tempered as well as austempered specimens of SG-01 has lower hardness value in comparison of that of in SG-02 because of more percentage of C, Mn, Ni, Cr, Mo and Si in SG-02 specimens that has tendency of strengthening solid solution of ferrite in ductile cast iron.

Fig. 4.4: shows the variation of weight loss with variation of applied load for SG-01 specimens. It can be noticed that annealed and quenched & tempered specimen behave in similar manner and that of normalized and austempered specimens are also same. The as-cast specimen behaved differently, when load is increased from 10N to 30N there is drastic drop in %weight loss but on further increase in load to 50N there is a slight increase in weight loss observed. In normalized and austempered specimens it was observed that %weight loss decreasing with increase in load and reached a negative value, that can be interpreted as %weight gain and can be attribute to the fact that under this high load for 7.54m long distance run oxide layers were formed on the surface which is evident from the EDAX analysis. On the other hand annealed and quench & tempered specimen appeared to have increase in % weight loss with increase in load.

At the same time when we look forward to the wear system response for alloy SG-02 it was observed that as-cast and austempered specimens showed marginal variation in its behaviour i.e., between 10N and 30Nload there was reduction in %weight loss and again marginal increase when load is further increased from 30N to 50N. The normalized and quench & tempered specimen appeared to lose weight continuously as the load in increased from 10N to 50N. The behaviour of annealed specimen is like to that of austempered and as-cast specimen but there is not such large variation observed.

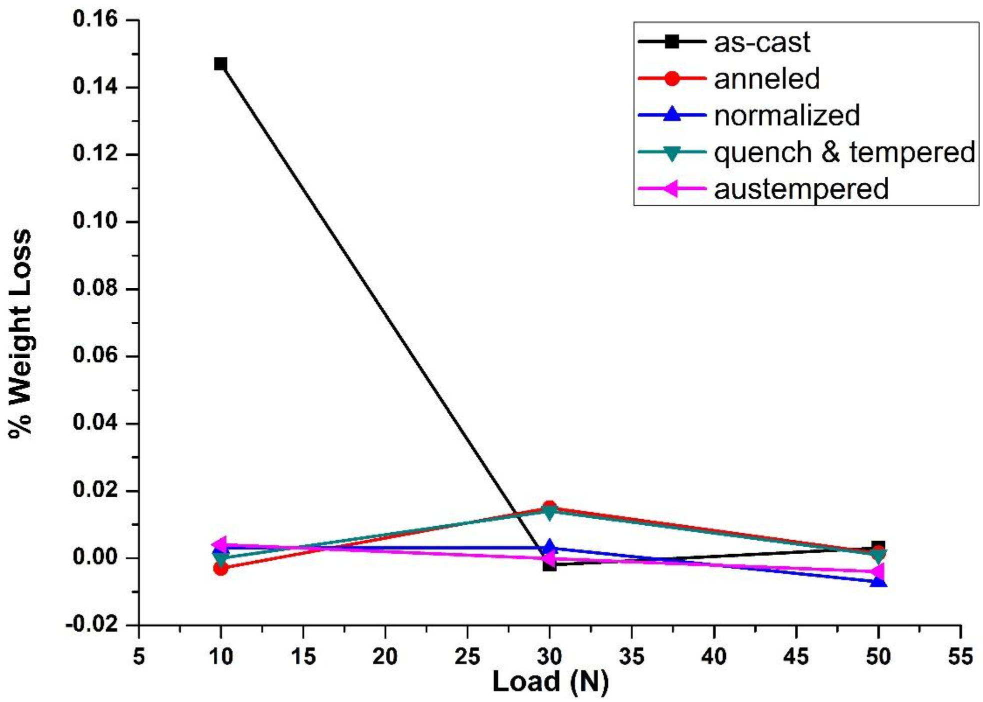


Fig. 4.4: Load vs. Weight loss for different hardness level of SG-01

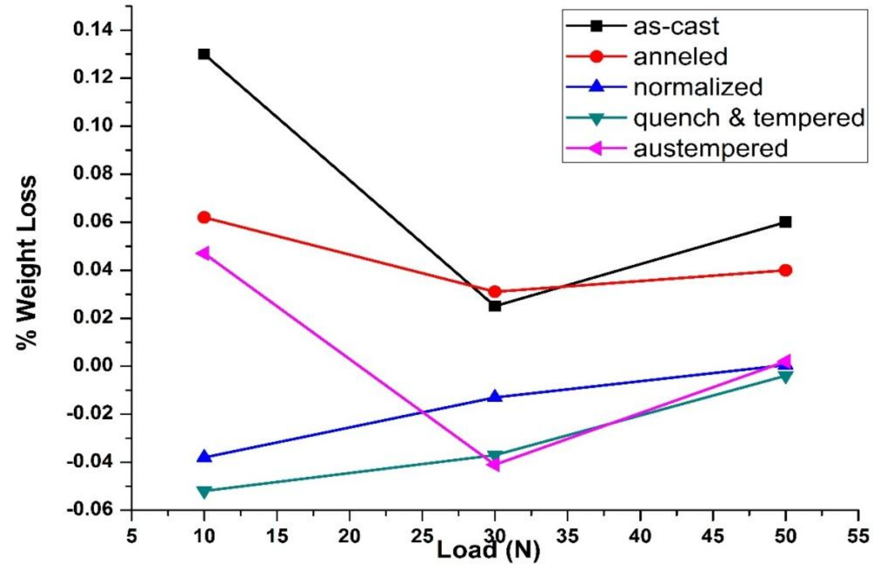
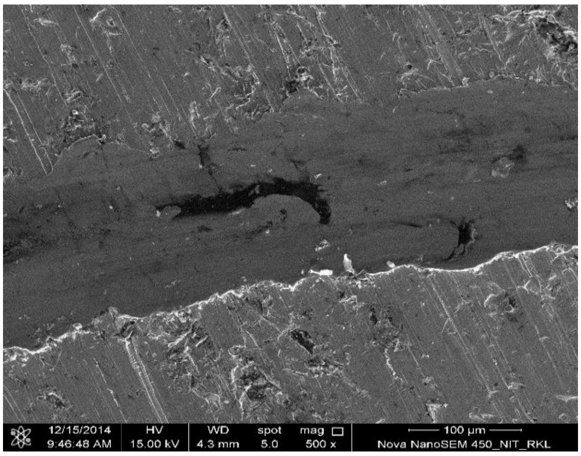


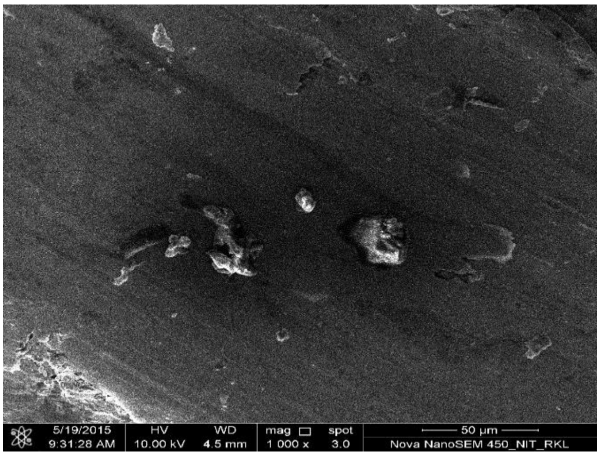
Fig. 4.5: Load vs. Weight loss for different hardness level of SG-02

4.4. Wear Mechanism:

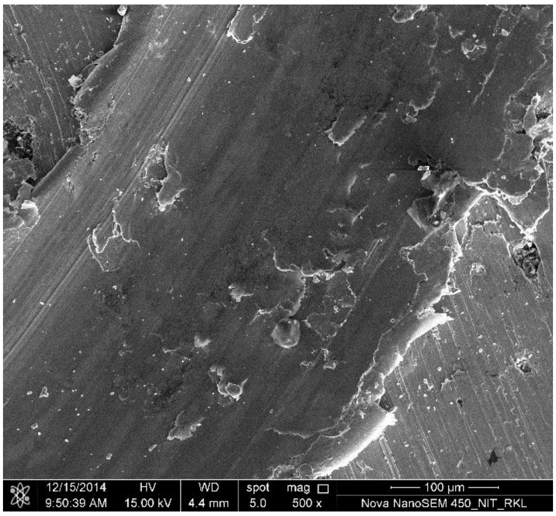
Investigation of wear mechanism of As-cast and heat treated samples are done with the help of FESEM. As a result of which the following wear tracks are obtained.



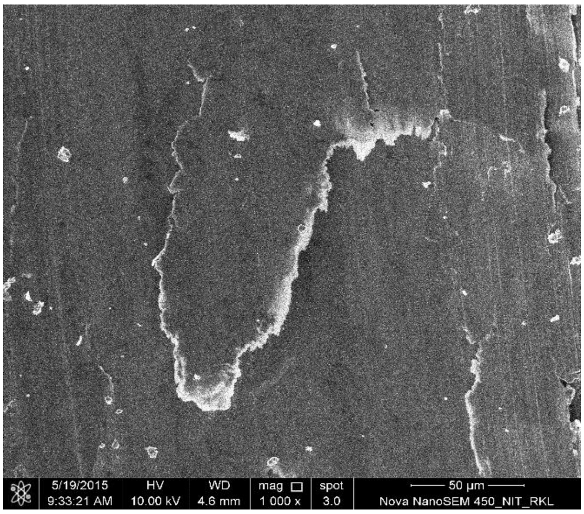
(1) As-cast SG-01 specimen10N



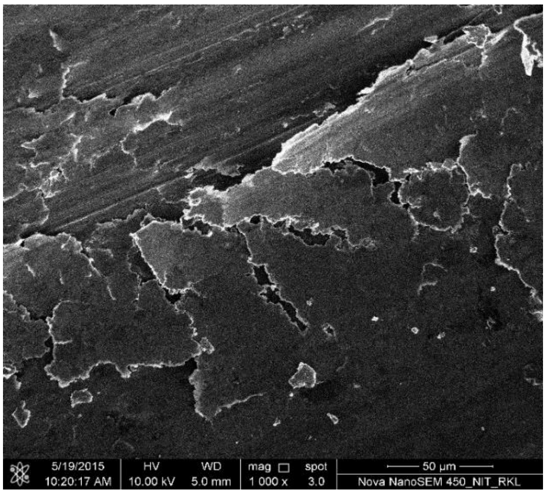
(2) A-cast SG-02 10N



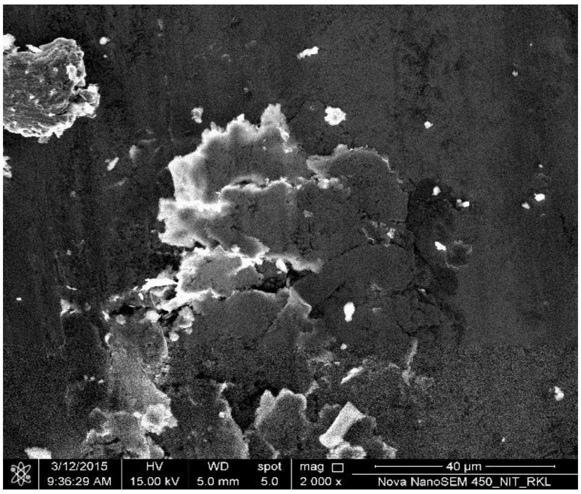
(3)As-cast SG-0130N



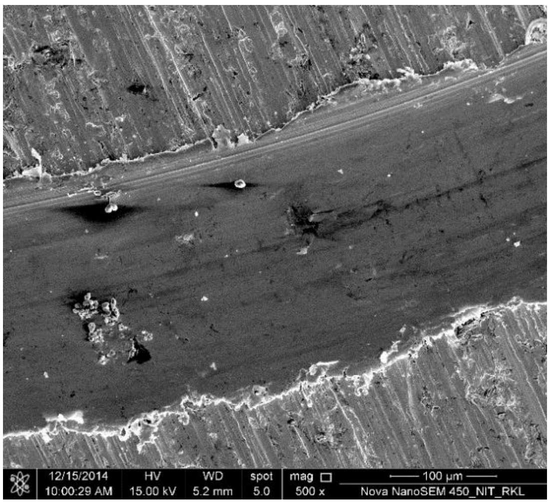
(4)As-cast SG-02 30N



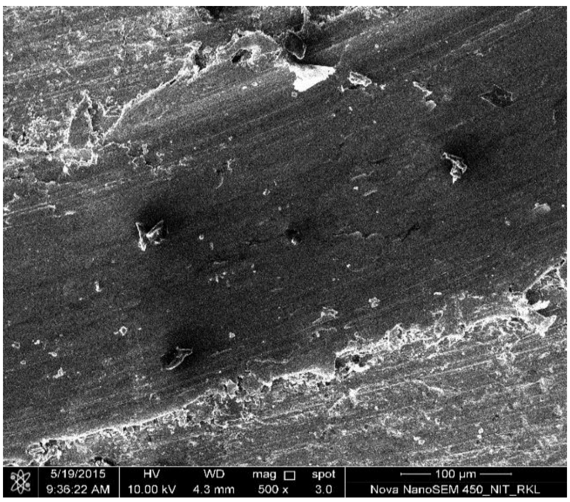
(5)As-cast SG-01 Specimen 50N



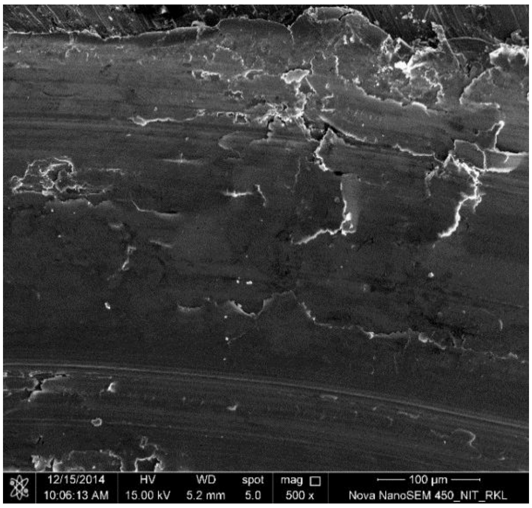
(6) As-cast SG-02 Specimen 50N



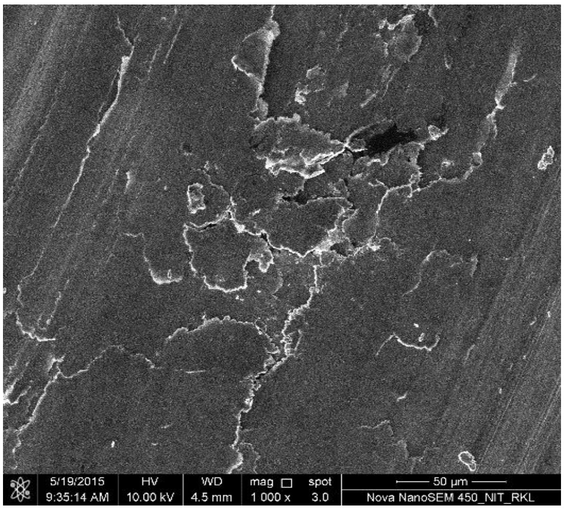
(7) Annealed SG-01 Specimen 10N



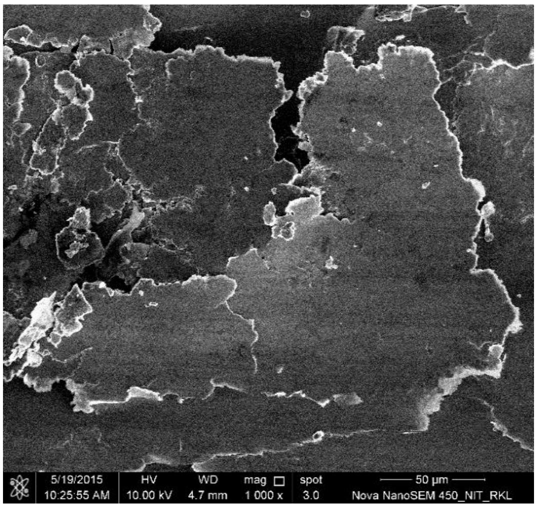
(8) Annealed SG-02 Specimen 10N



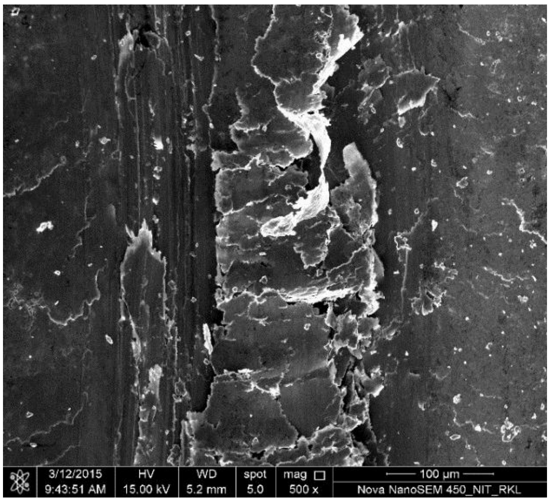
(9) Annealed SG-01 Specimen 30N



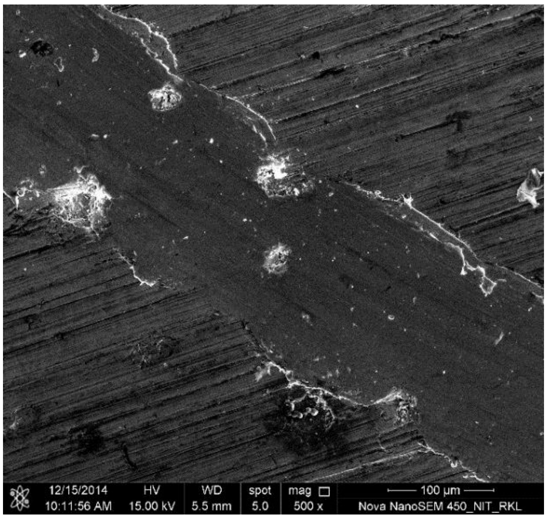
(10) Annealed SG-02 Specimen 30N



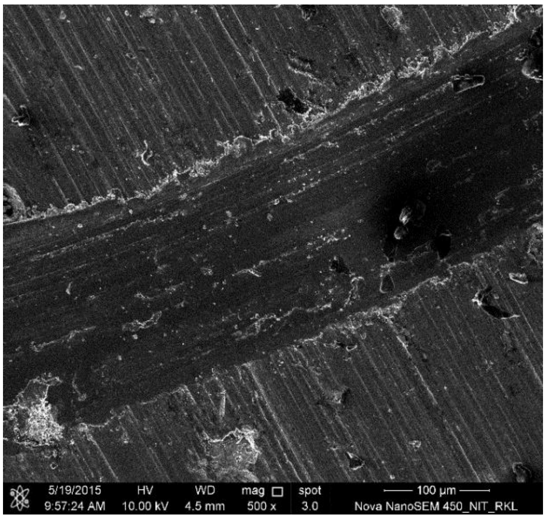
(11)Annealed SG-01 Specimen 50N



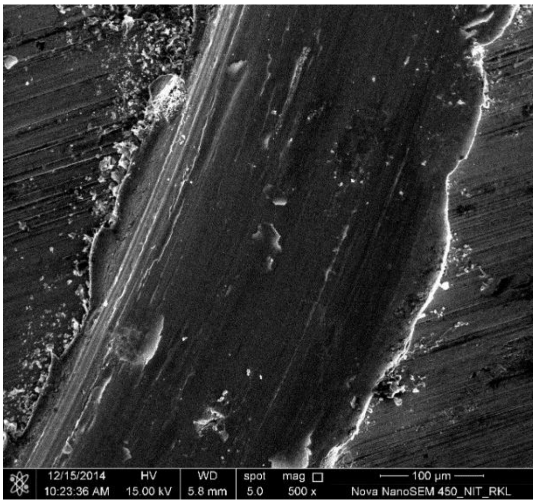
(12) Annealed SG-02 Specimen 50N

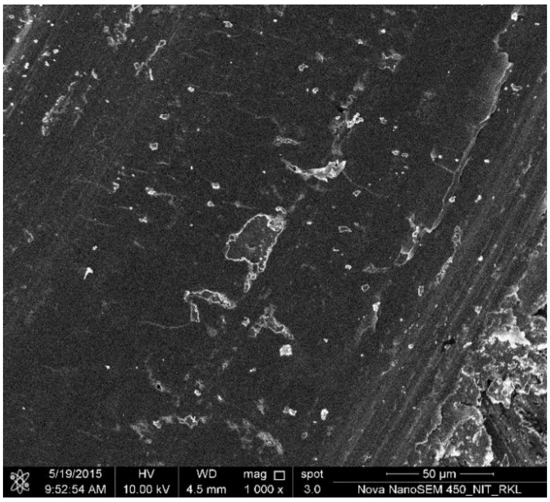


(13)Austempered SG-01 specimen 10N

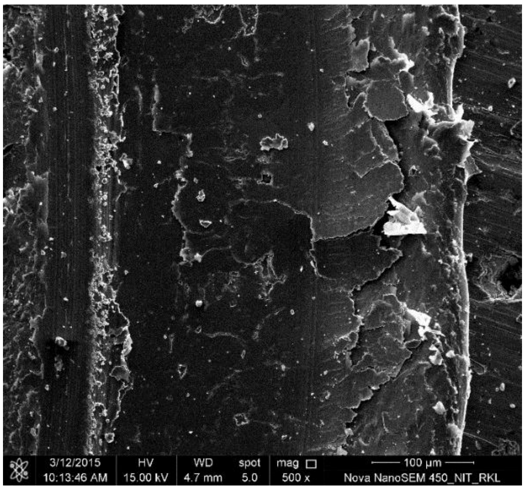


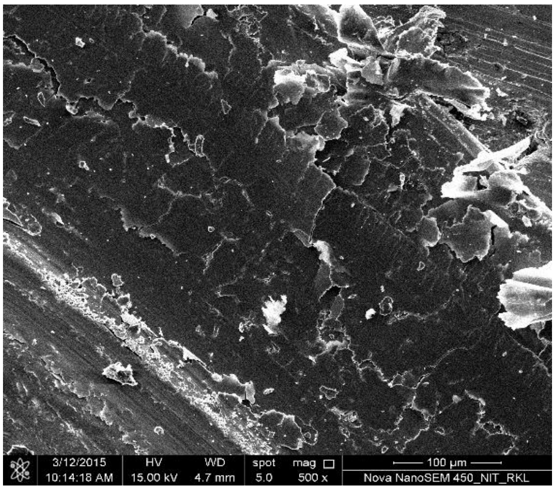
(14)Austempered SG-02 specimen 10N



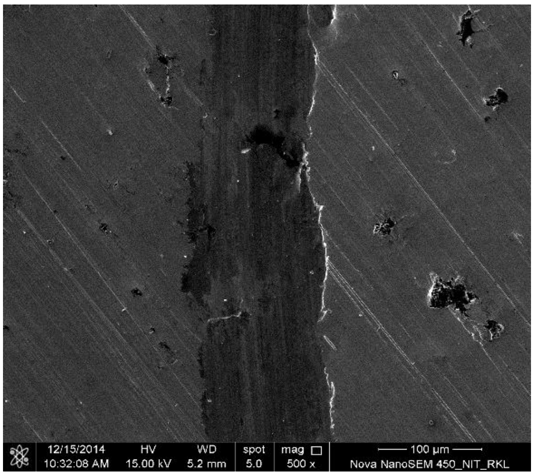


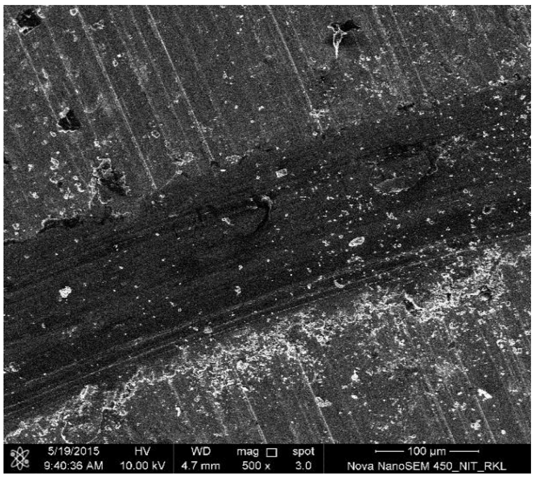
(15) Austempered SG-01 specimen30N (16) Austempered SG-02 specimen30N



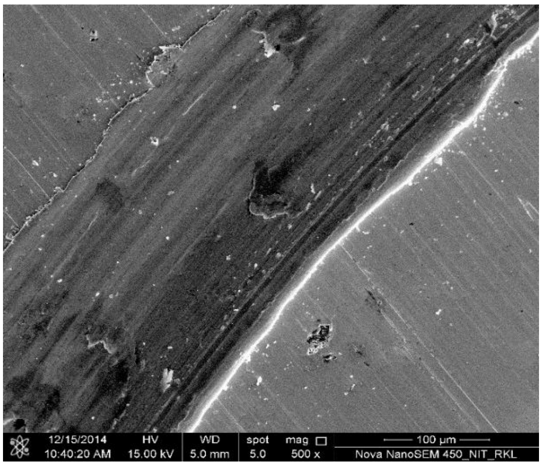


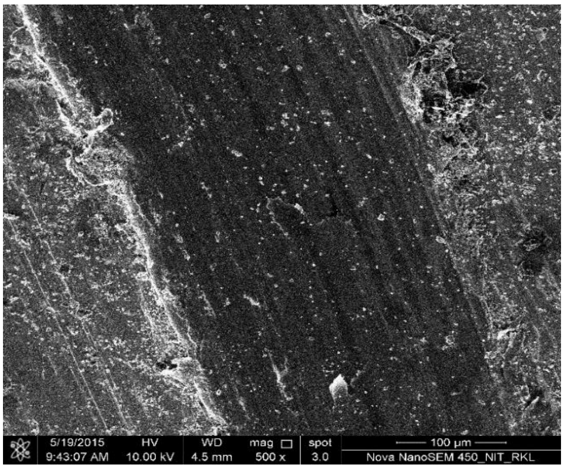
(17) Austempered SG-01 specimen 50N (18) Austempered SG-02 specimen 50N





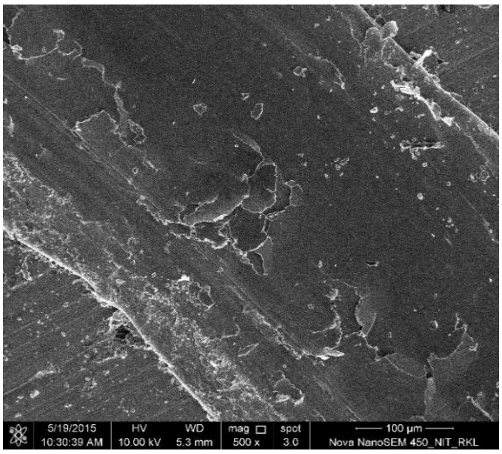
(19) Normalized SG-01 specimen 10N (20) Normalized SG-01 specimen 10N

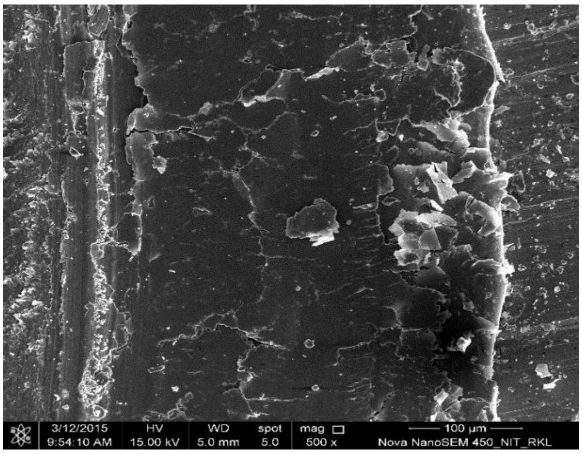




(21) Normalized SG-01 specimen 30N

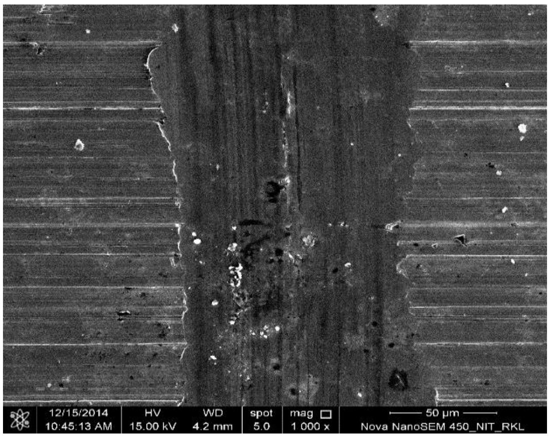
(22) Normalized SG-02 specimen 30N

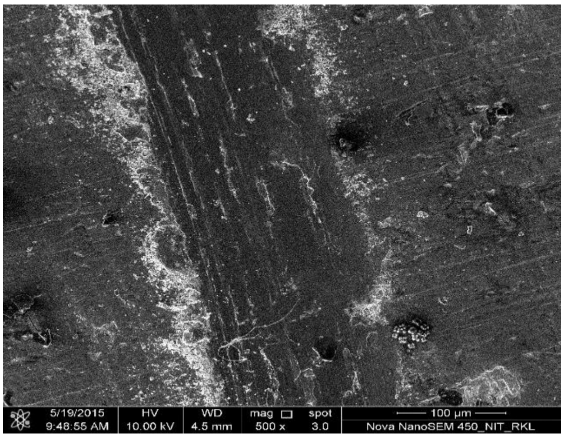




(23)Normalized SG-01 specimen 50N

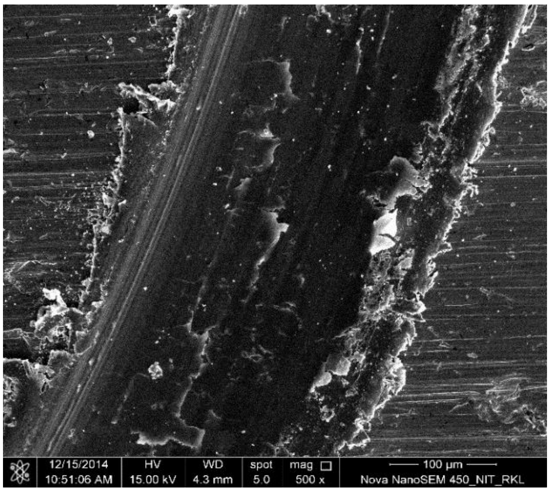
(24) Normalized SG-02 specimen 50N



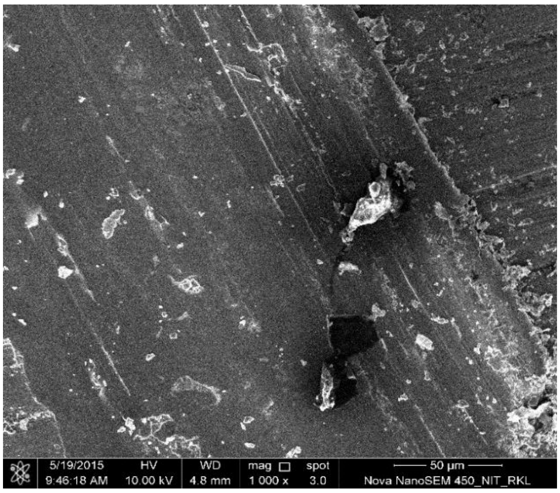


(25)Tempered SG-01 Specimen 10N

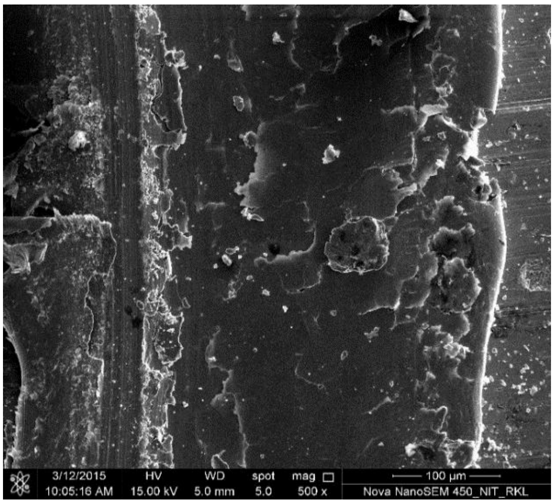
(26) Tempered SG-02 Specimen 10N



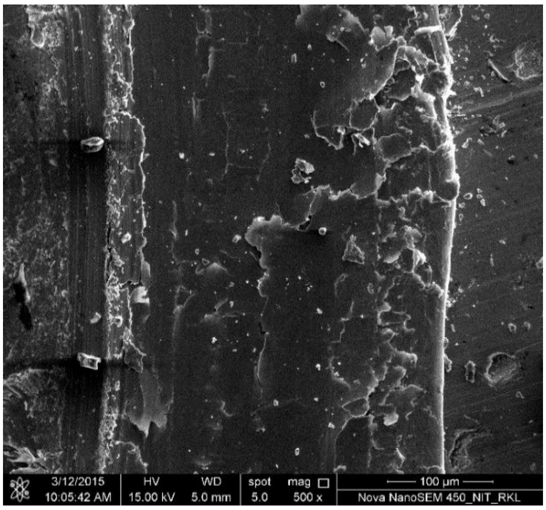
(27)Tempered SG-01 Specimen 30N



(28) Tempered SG-01 Specimen 30N



(29) Tempered SG-01 Specimen 50N



(30) Tempered SG-02 Specimen 50N

Fig.4.6. Worn surfaces of different specimen at varying load

It is clear from the figures above that at 10N load for every specimen the worn surface flat and very small delaminated layers were observed except normalized specimen which showed abrasive type of wear distinguished by the presence of abrasive particles formed from the worn surface itself due to higher hardness. On further increase in load to 30N softer materials were observed to have clear visible distinct delaminated layers whereas harder matrices appeared to have cracks over the worn surface signifying plastic deformation mechanism. At

30N also there is some abrasive particles observed over the worn surface of normalized specimen. When load is increased to 50N all the specimens at certain point reach their plastic stage and big cracks over worn surface can be seen. The presence of oxide layers as mentioned in previous section causing weight gain can be seen in the figure (21).

Chapter 5
Conclusions

5. Conclusions

The wear behaviour of as-cast and heat treated specimens were investigated taking two different grades of alloyed ductile iron. The conclusions drawn from above study are as follows;

1. Application of annealing, normalizing, quench & tempering and austempering heat treatment transformed the as-cast pearlitic/ferritic and ferritic matrix of alloy SG-01 and SG-02 respectively to fully ferritic, pearlitic/ferritic, tempered martensitic and coarse upper bainitic matrices resulting increased hardness. The hardness value of alloy SG-02 in Tempered and Austempered case is found to be higher than that of alloy SG-01 due to the presence of higher Si along with Mo and Cr content that stabilizes and strengthens the proeutectoid ferrite.
2. Harder matrices observed to have good wear resistance irrespective to change in load where as softer matrices doesn’t show decrease in wear rate at 30N and further increment in weight loss at 50N.
3. Quench and tempered specimens for both alloys appeared to be consistent irrespective to alloying addition when operated under different loading condition.
4. Adhesive wear is the main wear mechanism in every case justified by the presence of delaminated layer and plastically deformed surface cracks except normalized specimen operated under 10N and 30N which showed abrasive particles of worn material due to higher hardness.

Chapter 6
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